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ORIGINAL ARTICLE

Thermal parameters of UHPC in case of fire: an approach to the Brazilian standard ABNT NBR 15200

Parâmetros térmicos do UHPC em situação de incêndio: uma abordagem à norma brasileira ABNT NBR 15200

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Abstract: Ultra-high-performance concrete (UHPC) has exceptional mechanical properties at room temperature. However, there are no standardized thermal procedures proposed by ABNT NBR 15200 to characterize UHPC at high temperatures, such as in the case of fire. This is due to the lack of research on the subject, leaving gaps for experimental and numerical investigations. Based on experimental analyzes on standardized, small-scale specimens, this research collects a set of parametric data for UHPC at high temperatures. Thermal diffusivity, thermal conductivity, thermal expansion and specific heat as thermal parameters were defined for different temperature ranges. The results were compared with other structural concretes proposed in the literature (NSC, HSC and UHSC). The UHPC exhibited a particular fire behavior. Compared to NSC, HSC and UHSC, the thermal expansion and mechanical parameters of UHPC are less affected at high temperatures, but its thermal conductivity and mass loss are higher. UHPC also has the highest specific heat compared to other concretes. The thermal field of UHPC tends to be higher compared to the other concretes.

Keywords: UHPC, thermal properties, structures in fire, ABNT NBR 15200.

Resumo: O concreto de ultra alto desempenho (UHPC) possui excelentes propriedades mecânicas à temperatura ambiente. Entretanto, não existem métodos padronizados propostos pela ABNT NBR 15200 para caracterizar UHPC em altas temperaturas, como no caso de incêndio. Isso se deve à falta de pesquisas sobre o tema, deixando lacunas para investigações experimentais e numéricas. Com base em análises experimentais em amostras padronizadas e de pequena escala, esta pesquisa coletou um conjunto de dados paramétricos para o UHPC em altas temperaturas. Difusividade térmica, condutividade térmica, deformação térmica e calor específico como parâmetros térmicos foram definidos para diferentes faixas de temperatura. Os resultados foram comparados com outros concretos estruturais propostos na literatura (concreto convencional, concreto de alta resistência e concreto de ultra alta resistência). O UHPC exibiu um comportamento particular ao fogo. Comparado ao concreto convencional, concreto de alta resistência e concreto de ultra alta resistência, a expansão térmica e os parâmetros mecânicos do UHPC são menos afetados no incêndio, mas sua condutividade térmica e perda de massa são maiores. O UHPC também possui o calor específico mais alto em comparação com outros concretos. O campo térmico do UHPC tende a ser maior em comparação aos demais concretos.

Palavras-chave: UHPC, propriedades térmicas, estruturas em situação de incêndio, ABNT NBR 15200.

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1 INTRODUCTION

Ultra-high-performance concrete (UHPC, a term introduced by de Larrard and Sedran [1]) is an improved fiber-reinforced and cementitious concrete with exceptional mechanical properties at room temperature. The specified compressive strength must be in the range of 120 to 250 MPa, as recommended by ASTM C1856 [2]. The tensile strength must be in the range of 15 to 20 MPa according to Mishra and Singh [3]. Their durability is exceptional as explained by Amran et al. [4] and Alkaysi et al. [5]. As reported by Wang et al. [6], UHPC has a compressive strength that is three to sixteen times higher than that of NSC. According to Shi et al. [7], UHPC has a low weight/volume ratio, a water/cement ratio (w/c) between 0.15 and 0.25, a high cement content and consists of aggregates, fibers and superplasticizer. The matrix is dense and has few interconnecting pores, making it an attractive choice for chemically aggressive environments.

According to Amran et al. [4] and Park et al. [8], a continuous increase in the use of UHPC in concrete structures is expected. The application of UHPC has attracted interest worldwide, including in countries such as Austria, Australia, New Zealand, South Korea, Germany, Italy, France, Canada, Japan, Malaysia, the Netherlands, Slovenia and also the United States [4]. In these countries, reinforced UHPC structures are often used in high-rise buildings where high mechanical performance is required, but also where there are more stringent fire safety requirements.

Due to its mechanical properties, UHPC is a perfect material for applications where strength is a key factor and concrete members need to be smaller, thinner and more esthetically pleasing, as described by Yang et al. [9] and Mousavinejad and Sammak [10]. However, according to Amran et al. [4], UHPC members are more sensitive to high temperatures as they have smaller cross-sections and harder material properties compared to NSC, which can lead to spalling. The high thermal conductivity of the material leads to rapid heat transfer in the cross-section of UHPC structures.

Regarding the design of RC (Reinforced Concrete) structures under fire conditions, the behavior of concrete at high temperatures must be known. According to Zhu et al. [11], there is not much research on UHPC behavior at high temperatures. Studies by Xiong and Liew [12], Li et al. [13], Poon et al. [14], Kodur and Sultan [15], and Shin et al. [16] show that high-strength concrete (HSC) does not have the same fire behavior as normal-strength concrete (NSC) and is prone to spalling, as stated by Amran et al. [4], Ullah et al. [17], and Akca and Özyurt Zihnioglu [18]. According to Liang et al. [19] and Kalifa et al. [20], spalling occurs more frequently in UHPCs than in NSCs due to their dense structure and limited permeability due to their SF (Silica fume) content and lower w/c ratio. The majority of the few research dedicated to the study of UHPC at high temperatures aimed to comprehend the phenomenon of spalling [12], [18], [19], [21]–[26].

The spalling of UHPC is a problem at the structural level [4]. The location, depth and timing of spalling are highly unpredictable. UHPC beams have a small cross-sectional area, and the steel reinforcement could be directly exposed to fire, as described by Ozawa et al. [27]. According to Qin et al. [28], fire design and fire resistance analysis cannot rely on the results of fire tests conducted on UHPC members that exhibited spalling. In addition, the mechanical properties of UHPC decrease at high temperatures. UHPC specimens exposed to 400 °C show a reduction in their compressive strength [29], which affects the fire design of these structures.

There are no standardized procedures to design UHPC structures in fire situation. The EN 1992-1.2 [30], ACI-318 [31], AS 3600 [32], NZS 3101-1 [33], and ABNT NBR 15200 [34] do not provide thermomechanical values for RC structures fire design with concrete compressive strength greater than 100 MPa. There are few studies on this topic, and the fire behavior of UHPC is not well reported in the literature. Few studies have attempted to define the thermal properties of UHPC in high temperatures. In this context, authors such as Ullah et al. [17] do not recommend the use of UHPC in situations where fire design is demanded, since its thermal behavior is not well known.

Authors such as Du et al. [35], Wille and Parra-Montesinos [36] and Habel et al. [37] believe that UHPC is one of the most promising building materials for the future, but others, including Zhu et al. [11] and Ullah et al. [17], question its sensitivity to fire. According to SFPE [38], the fire performance of structures depends on the high-temperature properties of their materials. Huo et al. [39] have shown that NSC structures can exhibit better fire performance than UHPC, which reinforces concerns about the applicability of UHPC as a structural material.

Only a few recent UHPC researches analyze the fire behavior. For example, Zhang et al. [40] investigated the mechanical behavior of RC columns with UHPC jacket at room temperature; Tian et al. [41] and Zhou et al. [42] investigated the performance of UHPC under cyclic loading; Zhang et al. [43] studied the flexural behavior of UHPC beams; Zhang et al. [44] studied the use of UHPC with recycled fine concrete; Li et al. [45] studied the mechanical properties of UHPC with different types of cement; Cui et al. [46] studied the use of expansion agents in the concrete mix; and others.

The literature review proposed in the study by Zhu et al. [11] shows that there are few studies that propose thermal parameters for UHPC in different temperature ranges, such as the one proposed by Kodur et al. [47]. The authors investigated thermal and physical properties as conductivity, specific heat, mass loss and expansion. The UHPC studied by Kodur et al. [47] with f_c value between 164 and 178 MPa contains SF (silica fume), silica sand, PP (polypropylene) and steel fibers, slag and CA (coarse aggregate). Yang et al. [48] already show that CA reduces the thermal field of UHPC, i.e., UHPC without CA has a much larger temperature gradient than UHPC with CA. The UHPC in this study does not contain CA, but PVA (Polyvinyl acetate) fibers and a 750-day curing of the concrete, which makes this study a precedent. UHPC without CA has not yet been evaluated in the literature.

Compared to NSC, UHPC has 0.4 to 0.5 times higher specific heat capacity and 1.–5 to 2.0 times higher thermal conductivity, as described by Zheng et al. [49]. According to Algourdin et al. [50], the ability of UHPC to prevent heat transfer to the interior decreases with increasing steel fiber content. When the steel fiber concentration exceeds 2%, the UHPC structural member loses some of its fire resistance due to the increased thermal conductivity of the fibers and the rapid internal heat transfer caused by the fibers, as described by Wang et al. [51]. However, there is limited research on this topic, which highlights the need for further studies on this subject [49].

Due to the lack of literature results and also the standardized methodology presented above, the thermal properties of UHPC without CA were determined in this study. The thermal parameters determined were conductivity, diffusivity, specific heat and thermal expansion. In order to fill a gap in the standardized procedures, equations, graphs, and also tables were provided for the application of these parameters in the fire design of these structures.

2 MATERIALS AND EXPERIMENTAL PROGRAM

The materials used to build the UHPC and the test-methods used to characterize UHPC in each temperature range are shown.

2.1 Materials

The cement used was a high initial-resistance type that contains low chemical additions. It is a Portland cement used in Brazil classified as CP-V ARI by ABNT NBR 16697 [52]. Silica fume (88.5% silicon contained) and fly ash (50.0% of silicon content) were used, with specific gravity of 350 kg/m^3 and 210 kg/m^3, respectively. Silica fume acts as a microfiller. It also reacts with calcium hydroxide increasing the final strength.

A natural washed river sand quartz with 260 kg/m^3 was incorporated. The steel fiber had a length of 25 mm and a diameter of 0.75 mm, with tensile strength of 1100 MPa and modulus of elasticity of 210 GPa. To avoid explosive spalling of the concrete, PVA fibers (polyvinyl acetate) with a length of 12 mm and a diameter of 0.04 mm, tensile strength of 1600 MPa and modulus of elasticity of 41 GPa were added (preliminary experimental fire tests carried out by the authors on full-scale UHPC columns showed explosive spalling of the UHPC).

These results are presented in Christ et al. [53]). Superplasticizer additive based on polycarboxylates was incorporated to improve the workability of the concrete. The UHPC production and mix were according to Christ et al. [54] method.

The concrete mix design is presented Table 1.

Table 1. Concrete mix design

Material	Unit content (kg/m^3)	Ratio to cement content
Cement	488	1.00
Silica fume	268	0.55
Fly ash	235	0.48
Natural sand (fine aggregate)	1025	2.10
Steel fiber	120	0.25
PVA fiber	6	0.02
Chemical additive	17.6	0.03
Water	178	0.36

The average compression strength of the concrete at 28, 150 and 750 days were 108.0±3.1, 146.4±3.8 and 162.4±4.1 MPa, respectively. The average elastic modulus was 41.4, 44.0 and 46.1 GPa at, respectively, 28, 150 and 750 days. These results were obtained by testing a concrete cylinder with a dimension of 150×300 mm (diameter × length) made according to ASTM C470 [55] and ABNT NBR 5738 [56]. The concrete compressive strength test method was according to ASTM C39 [57] and ABNT NBR 5739 [58]. The elastic modulus test method followed ASTM C469 [59] and ABNT NBR 8522 [60]. The concrete specimens are produced in accordance to ASTM C31 [61] and ASTM C192 [62] and ABNT NBR 5738 [56].

2.2 Thermal properties definitions

The thermal diffusivity, specific heat, thermal conductivity and thermal elongation data were determined as below. For each experimental test proposed, two small-scale test specimens (test and counter-test) were used with the same concrete mixture.

2.2.1 Diffusivity

The thermal diffusivity of UHPC was obtained according to the Flash Method specified at ASTM E1461 [63]. The method is used to measure values of thermal diffusivity of a wide range of solid materials. The results were obtained by testing concrete cylinders with a dimension of 12.7×2.5 mm (diameter × thickness) in accordance with ASTM E1461-13 [63] prescriptions. The UHPC specimens were heated to 100, 200, 300, 400, 500 and 600°C. The testing equipment was a thermal diffusivity analyzer with a temperature range from -125°C to 600°C, a thermal diffusivity measurement ranges from 0.01mm^2/s to 1000mm^2/s and a thermal conductivity range from 0.1W/m·°C to 2000W/m·°C.

With the thermal diffusivity (α) results and with the density in fire (ρ) it is possible to obtain the specific heat (C_p) and thermal conductivity (k) according to Equation 1.

$$\alpha = \frac{k}{\rho \cdot C_p} \tag{1}$$

The experimental test gives information about the result of thermal diffusivity and specific heat. The density results are obtained by measuring the specimen before and after the heating procedure. Thermal conductivity results are obtained in parallel, determined directly by the computing software installed on the testing machine.

2.2.2 Specific heat

According to the thermal diffusivity results and according to Equation 1, the specific heat values were defined for the same temperature ranges as in section 2.2.1.

2.2.3 Conductivity

According to the results of thermal diffusivity and Equation 1, the thermal conductivity values were defined for the same temperature ranges as in section 2.2.1.

2.2.4 Thermal elongation

Horizontal dilatometers were used to determine the linear expansion of UHPC specimens according to the ASTM E228 [64]. Temperature and length changes are the factors (testing variables) used to record the expansion data. The experimental results were obtained by testing prismatic specimens with dimensions 10×50×10 mm (i.e., width, length, thickness). A cylindrical furnace is set to surround the specimen uniformly from all sides and to comply with the specified heating program. The UHPC specimen is heated at a pre-programmed heating rate of 5°C/min, and then the linear expansion is monitored at each temperature. Temperatures of 100, 200, 300, 400, 500 and 600°C were considered.

2.3 Specimen heating temperature

A short pulse with high radiation intensity is used to evaluate the thermal properties of a small-scale UHPC specimens. The energy of the pulse is absorbed by the front side of the specimen, and the corresponding temperature rise on the back side (thermogram) is then measured. The value of thermal diffusivity is calculated based on the thickness of the specimen and the time it takes for the temperature rise on the back surface to reach a certain percentage of the maximum value. The thermal diffusivity is estimated from a dynamic back surface temperature curve (as shown in Figure 1), where T is the temperature in each increment and T_{max} is the highest desired temperature. The thermal diffusivity, specific heat and conductivity parameters were determined according to Figure 1.

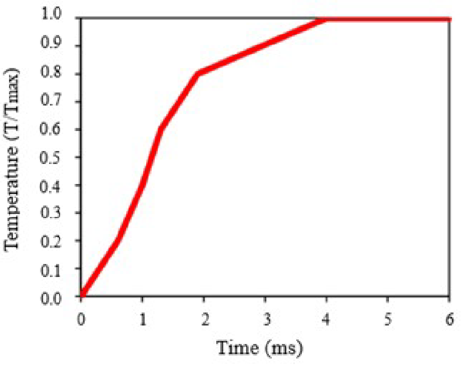


Figure 1. Heating curve used to define thermal properties.

2.4 Correlation with the standard procedures and references

The results (data available in this research) were compared with those proposed by the references. When possible, the data were compared with normal-strength (NSC), high-strength (HSC), ultra-high-strength (UHSC) and, when available, ultra-high-performance (UHPC) concrete similar to this research. Graphs were proposed with the UHPC results of this research. From these, new equations were extracted.

2.3 Notes for testing UHPC at high temperatures

The first fire tests with UHPC test specimens were evaluated at 28 and 150 days after their construction. However, in these ages, there was explosive spalling of the concrete. In the first case, there was spalling when the specimen was heated to around 100°C. In the second case, when heated to 300°C. After 700 days, the specimens showed no more concrete spalling when heated to 800°C. This justifies carrying out the tests with 750 days.

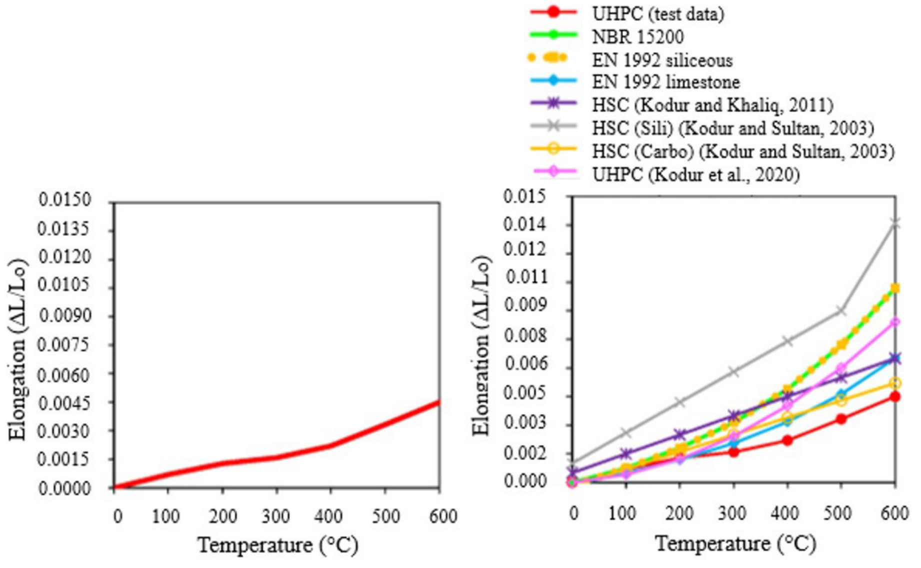
The low porosity of UHPC prevents internal dissipation of water vapor produced during heating. It is necessary that fire tests be carried out on aged concrete. Due to the high mechanical strength of UPC, the amount of internal water vapor is high and the concrete spalling is explosive. These results are in agreement with Zhu et al. [11] and Ullah et al. [17], who showed that UHPC is more susceptible to spalling in fire than NSC. However, it is important to highlight that the spalling decreases with age, as the internal humidity of the concrete tends to reduce with age, as shown by Manica et al. [65] and in accordance the previous results of this research.

3 RESULTS AND DISCUSSION

The results of this research are presented.

3.1.1 Thermal elongation

Figure 2a show the thermal elongation ($\Delta L/L_o$) results of UHPC for different temperature ranges. Figure 2b and Table 2 shows the comparison of these results with references.



(a) UHPC (test data) **(b)** UHPC (test data) and references

Figure 2. Thermal elongation at high temperatures.

Table 2. Thermal elongation: correlation between UHPC and references

	Thermal elongation $\Delta L/L_o$ ($\times 10^{-3}$)							
Temperature (°C)	**UHPC Test Data**	**ABNT NBR 15200**	**EN 1992 (NSC) (Sili) (C20/50)**	**EN 1992 (NSC) (Lime) (C20/50)**	**HSC (Kodur and Khaliq [66])**	**HSC – Sili (Kodur and Sultan [15])**	**HSC – Carbo (Kodur and Sultan [15])**	**UHPC (Kodur et al. [47])**
	(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	0.71	0.74	0.74	0.50	2.30	2.60	0.70	0.41
200	1.28	1.80	1.80	1.19	4.20	4.20	1.60	1.21
300	1.59	3.14	3.14	2.06	5.80	5.80	2.50	2.41
400	2.20	4.89	4.89	3.18	7.40	7.40	3.40	4.01
500	3.33	7.20	7.20	4.63	9.00	9.00	4.30	6.01
600	4.50	10.2	10.2	6.50	13.6	13.6	5.20	8.41

UHPC (Table 2a) has positive thermal elongation when exposed to high temperatures, as with other concretes (Table 2b-h). The UHPC of this research had the lowest $\Delta L/L_o$ value in relation to the others. Up to 100°C thermal elongation can be related to the loss of humidity (free water) in the concrete. Between 300 and 500°C, values may be associated with and $Ca(OH)_2$ and CaO dehydration, as reported by Laneyrie et al. [25]. The lower expansion of UHPC (Table 2a) in relation to the other concretes (Table 2b-h) shows the influence of the coarse aggregate in this aspect. The values of ABNT NBR 15200 [34] are the same as those proposed by EN 1992 [30] for siliceous coarse aggregates. In relation to the UHPC tested by Kodur et al. [47], in addition to the aggregate, also the experimental procedure (see section 2).

3.1.2 Specific heat

Figure 3a show the specific heat results of UHPC in different temperature ranges. Figure 3b and Table 3 shows the comparison of these results with references.

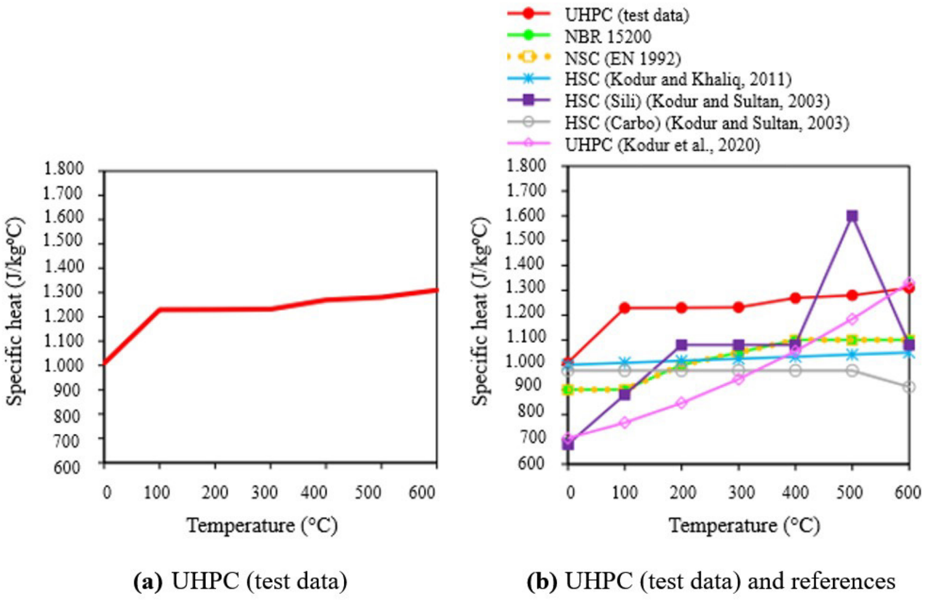


Figure 3. Specific at high temperatures.

Table 3. Specific heat: correlation between UHPC and references

	Specific heat (J/kg·°C)							
Temperature (°C)	UHPC Test Data	ABNT NBR 15200	EN 1992 (NSC) (Sili) (C20/50)	EN 1992 (NSC) (Lime) (C20/50)	HSC (Kodur and Khaliq, [66])	HSC – Sili (Kodur and Sultan [15])	HSC – Carbo (Kodur and Sultan [15])	UHPC (Kodur et al. [47])
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
25	1009	900	900	1104	1000	720	730	977
100	1229	900	900	-	1008	767	880	977
200	1230	1000	1000	-	1016	846	1080	977
300	1232	1050	1050	-	1025	942	1080	977
400	1269	1100	1100	-	1033	1055	1080	977
500	1280	1100	1100	1354	1041	1184	1600	977
600	1310	1100	1100	-	1050	1330	1089	911

In the UHPC specimens tested, the influence of internal moisture on the results was not considered. Therefore, in cases where it was possible, the UHPC data proposed in this study were also compared with corresponding results from the literature under dry conditions (i.e., without internal moisture).

Specific heat changes with temperature due to chemical and physical changes that occur in cement past and aggregates when in heating. Between 100°C–300°C, specific heat increases further due to the evaporation of moisture present in the remaining free water, in addition to the adsorbed and bonded water. In the range of 300-500°C, the C_p remains almost constant due to the decrease in humidity and $Ca(OH)_2$ decomposition. There is a small increase in C_p after this temperature due to the release of moisture from the decomposition of the C-S-H gel and significant deterioration of the microstructure within the concrete.

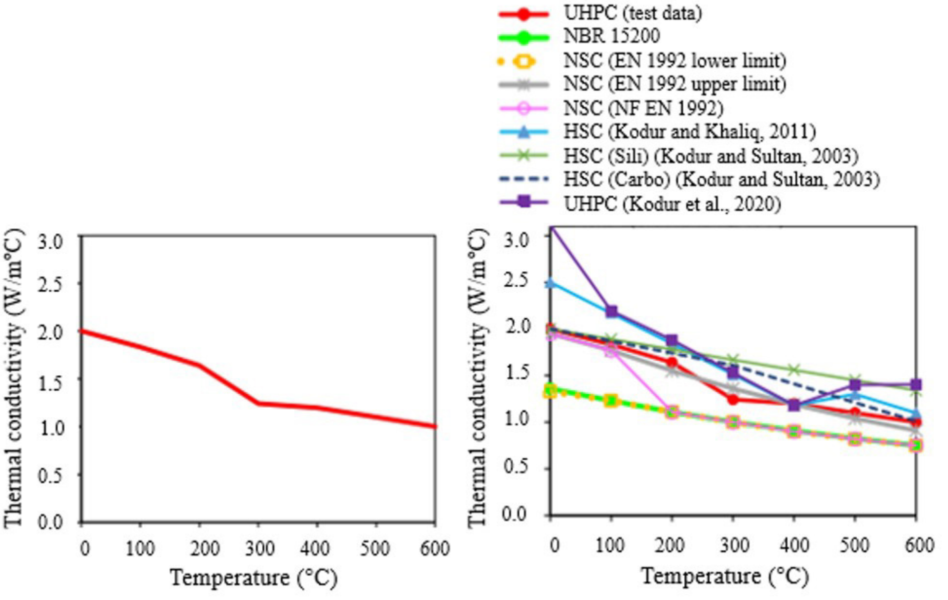
In the case of the UHPC, Figure 3a and Table 3a show that at 25°C its specific heat is 1009 J/kg·ºC. At the same temperature, these values are similar to those presented by Shin et al. [16] for NSC, by Kodur and Sultan [15] for HSC and Kodur et al. [47] by HSC with carbonate aggregate. The UHPC value at 25°C (Table 1a) was lower than those reported by ABNT NBR 15200 and EN 1992 for the NSC (Table 3b and 3c, respectively), for the UHPC evaluated by Kodur et al. [47] (Table 3f), and also for HSC with siliceous aggregates proposed by Kodur and Sultan [15] (Table 3g).

According to Figure 3a and Table 3a, at 100°C, the C_p of the UHPC tested increased to 1229 J/kg·ºC. At the end of the tests (600°C) the value was 1310 J/kg·ºC. For the equations proposed in section 5, the value of the specific heat in the range from 100 to 600°C was defined as the average of the C_p readings in this temperature range (i.e., Cp 1270 J/kg·ºC). This is a practical simplification of fire design since there is variability between the results, according to Table 3.

In the temperature range 100-600°C, the same interpretation and comparison made at 25°C between researches is preserved (Table 3a-f). However, the research of Kodur et al. [47] for UHPC (Table 3f) and Kodur and Sultan [15] (Table 3g) for HSC, which at initial temperatures (i.e., 25 °C) did not converge with the UHPC of this research, tends to converge at the end of analysis. Normally the UHPC of this research (Table 3a) has a specific heat relatively higher in relation to the others concretes. It can be attributed to the lower permeability and dense microstructure of UHPC that requires more heat for evaporation of water.

3.1.3 Conductivity

Figure 4a plots the thermal conductivity of UHPC for various temperature ranges. Figure 4b and Table 4 show the comparison of these results with bibliography.



(a) UHPC (test data) **(b)** UHPC (test data) and references

Figure 4. Thermal conductivity at high temperatures.

Table 4. Thermal conductivity: correlation between UHPC and references

Temperature (°C)	Thermal conductivity (W/m·°C)									
	UHPC Test Data	ABNT NBR 15200	NSC EN 1992 (lower limit)	NSC EN 1992 (upper limit)	NSC NF EN 1992	NSC (Shin et al. [16])	HSC (Kodur Khaliq [66])	UHPC (Kodur et al. [47])	HSC – Sili (Kodur and Sultan [15])	HSC – Carbo (Kodur and Sultan [15])
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
25	2.00	1.36	1.36	1.95	1.95	2.19	2.42	3.11	1.97	1.97
100	1.83	1.23	1.23	1.77	1.77	-	2.17	2.19	1.89	1.87
200	1.64	1.11	1.11	1.55	1.11	-	1.84	1.88	1.78	1.74
300	1.24	1.00	1.00	1.36	1.00	-	1.51	1.53	1.67	1.61
400	1.20	0.90	0.90	1.19	0.90	-	1.18	1.18	1.56	1.41
500	1.10	0.82	0.82	1.04	0.82	1.28	1.30	1.40	1.45	1.21
600	1.00	0.75	0.75	0.91	0.75	-	1.10	1.40	1.34	1.00

At temperatures above 100°C, free water begins to evaporate, and sometimes causing spalling. When the concrete temperature reaches about 300°C, the adsorbed water from the calcium silicate hydrate (C-S-H) gel and a part of the chemically bound water begin to evaporate. The concrete temperature further to 400°C causes decomposition of $Ca(OH)_2$ converting it into CaO and H_2O, increasing the moisture content of concrete.

Further increase in temperature beyond 500°C leads to decomposition of C-S-H and further deterioration of concrete and aggregate.

According to Figure 4b and Table 4, it can be seen that the UHPC in this research (Table 4a) are, respectively, 50.4%, 2.6% and 2.6% higher in relation to the NSC proposed by ABNT NBR 15200 [34] and EN 1992-1.2 [30] Table 4b-d) and NF EN 1992 [67] (Table 4e). Research by Kodur et al. [47] show that the UHPC had a conductivity 55% higher than those obtained in this research. After 300°C, the values between both researches tend to converge. In relation to the NSC proposed by the EN 1992-1.2, the UHPC tested by Kodur et al. [47] were 133.8% higher. The notable variability in these results is understandable, and can be attributed to varying moisture content, cement type, aggregate, test conditions and measurements techniques used in each research, as explain by Kodur et al. [47], [68] and Bazant and Kaplan [69].

4 PROPOSALS OF PROCEDURES FOR STRUCTURAL FIRE DESIGN

Due to the absence of UHPC-specifications in the ABNT NBR 15200 [34] standard, parametric data are proposed to support the fire-design of UHPC structures in case of fire. The proposed equations were derived from the proposed graphs (i.e., Figures 5 to 7 below). Since the graphs are rectilinear, the proposed equations are linear.

4.1 Thermal elongation

Figure 5 show the experimental data points with the proposed regression line, compared to the ABNT NBR 15200 [34] specification. Equation 2 is the proposed thermal elongation formulation for UHPC at different temperatures.

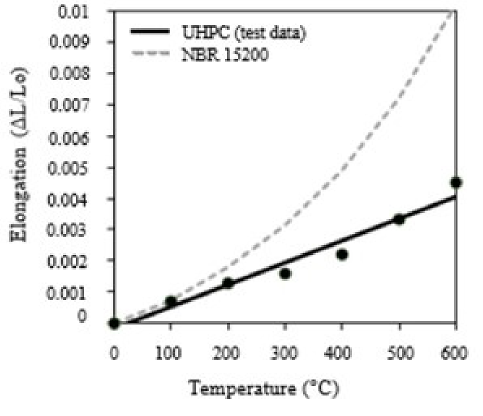


Figure 5. Results of thermal elongation values for UHPC.

$$\frac{\Delta L}{L_o} = 7\times10^{-6} \times \ T - 2\times10^{-4} \left(R^2 = 0.96\right) \tag{2}$$

Were T being the temperature in degrees Celsius (°C)

4.2 Specific heat

Figure 6 show the experimental data points with the proposed regression line, compared to the ABNT NBR 15200 [34] specification. Equation 3 is the proposed specific heat formulation for UHPC at different temperatures.

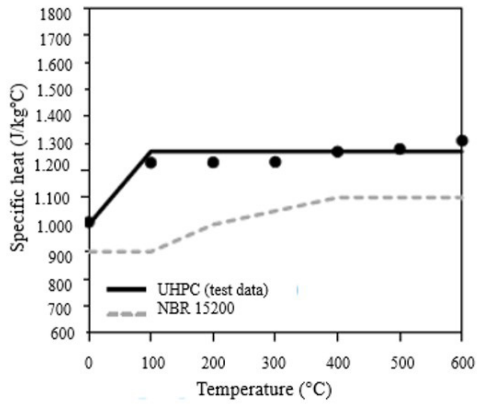


Figure 6. Proposal of specific heat values for UHPC.

$$C_p = 2.7 \times T + 1000 \, \left[J / kg \cdot {}^{\circ}C\right]\left(R^2 = 0.99\right) \; 25 \leq T < 100^{\circ}C$$
$$C_p = 1270 \qquad \left[J / kg \cdot {}^{\circ}C\right]\left(R^2 = 0.95\right) \; 100 \leq T < 600^{\circ}C \tag{3}$$

Were T being the temperature in degrees Celsius (°C)

4.3 Conductivity

Figure 7 show the experimental data points with the proposed regression line, compared to the ABNT NBR 15200 [34] specification. Equation 4 is proposed specific heat formulation for UHPC at different temperatures.

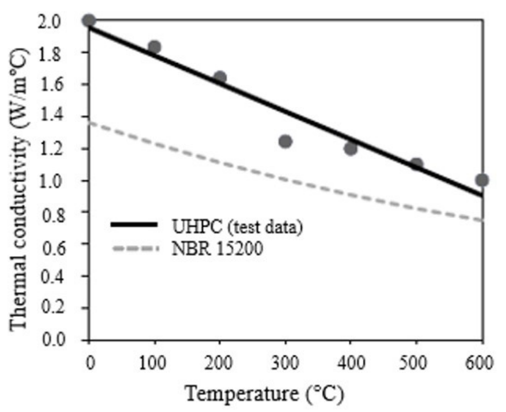


Figure 7. Proposal of thermal conductivity values for UHPC.

$$k_{\theta} = -1.8 \times 10^{-3} \times \; T + 1.95\left[W / m{\cdot}{}^{\circ}C\right] \left(R^2 = 0.95\right) \tag{4}$$

Were T being the temperature in degrees Celsius (°C)

4.4 General remarks on the proposed equations

The proposed equations were obtained by linear regression of the experimental data of the specimens tested in the laboratory. The values were compared with the data of ABNT NBR 15200, which were identical to EN 1992, without any adjustment for the materials used in Brazil. The thermal data presented by UHPC are used, for example, in numerical tests that evaluate the thermal field of reinforced concrete structures. They are fundamental data used to performing, e.g., thermal analyzes. Although the standard provides values up to 1000°C for normal strength concrete, only data up to 600°C were presented. This is due to the fact that experimental UHPC values were limited to 600°C. The proposed curves (and thus the equations) are very close to the experimentally obtained data. A limitation of this study (and thus of the proposed equations) is that the proposed curves were obtained with a single trace of UHPC. It is proposed to continue this study and test such data for other concrete mixtures. The proposed results are unprecedented, as there is no similar information in an international standard for fire design of UHPC structures, and also in the literature. According to Zhu et al. [11] and the literature review given in this study (section 1), this research represents an unprecedented investigation of the thermal data of UHPC without CA, made with the Brazilian materials, and their correlation with the ABNT NBR 15200 procedures. In addition, the study proposes new analytical equations to characterize these parameters for each temperature range.

4.5 Final remarks

Depending on the temperature to which the material (structure) is exposed, the proposed UHPC parameters change. It is assumed that these parameters are effective and do not fully describe the structure, since the thermal field and temperature distribution in a cross-section of a structure are not uniform. The performance of UHPC structures in fire scenarios should be evaluated in a future study using numerical FEA models using the proposed parameters or standards. Compared to NSC (according to the parameters EN 1992-1.2 and ABNT NBR 15200), UHPC showed higher thermal diffusivity. Probably, UHPC cross-section heats up more than NSC, which needs to be investigated in future studies.

5 CONCLUSIONS

The general conclusions of this paper are:

- This research demonstrated that UHPC specimens tested before 700 days are susceptible to concrete spalling at high temperatures;
- When compared to NSC (according to EN 1992-1.2 parameters), UHPC showed higher thermal diffusivity;
- With regard to thermal diffusivity, UHPC structures tend to have a higher thermal field in their cross-section compared to NSC;
- Thermal conductivity of UHPC is higher than the thermal conductivity of NSC, because UHPC contains steel fibers;
- When compared to NSC and HSC, the UHPC has the lowest thermal elongation values at different temperatures;
- UHPC has a higher specific heat value when compared to other concretes (NSC, HSC). This result can be explained because of the lower permeability and dense microstructure of UHPC that requires more heat for water evaporation;
- New equations were proposed to define the thermal, physical and mechanical parameters of UHPC at high temperatures. These equations are essential for researchers who intend to carry out numerical research with UHPC;
- As future research, it is necessary to test other concrete mixes, with different coarse aggregates and fiber contents and confirm the results here reported by testing program in other laboratories, to verify the repeatability of the results and the proposed equations.

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